
Lean Premixed/Prevaporized Combustion

A workshop held at
Lewis Research Center
Cleveland, Ohio
January 20-21, 1977

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Edited by
A.H. Lefebvre
Purdue University

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FOREWORD

The National Aeronautics and Space Administration is actively involved in programs directed toward reducing exhaust emissions from aircraft gas turbine engines. In order to achieve minimum emission levels it is necessary, among other things, to very carefully control the fuel vaporization, degree of fuel-air mixing, and the relative proportions of fuel and air directly involved in the combustion process. These ideas are all embodied in the lean premixed/prevaporized combustion concept. A two-day workshop was held at the NASA Lewis Research Center, Cleveland, Ohio, to provide an opportunity for combustion experts from government, universities, and industry to examine the status of this concept and its application to aircraft gas turbine engines. In addition, the NASA Stratospheric Cruise Emission Reduction Program was reviewed and comments regarding its technical merit were invited.

NASA participation in the workshop was limited to a liaison/advisor capacity and to a general review of its ongoing programs. This compilation contains the thoughts and recommendations of the workshop participants as arranged by the Workshop Chairman, Professor A. H. Lefebvre of Purdue University.

Larry A. Diehl
NASA Lewis Research Center
Workshop Organizer

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PREFACE

This workshop was conceived and sponsored by NASA Lewis Research Center as a means of bringing together combustion experts from government, universities, and industry to examine the status of the lean premixing/prevaporizing combustion concept and its application to the aircraft gas turbine for the reduction of pollutant emissions. Another objective was to review the NASA Stratospheric Cruise Emission Reduction Program (SCERP) and to invite comments on its technical merits.

Seventeen participants met for 2 days. They comprised eleven representatives from universities and six from industry, as listed in appendix A. Also in attendance were a number of observers and Lewis personnel involved in the SCERP program.

The proceedings opened with welcoming statements by the Chairman (Prof. A. H. Lefebvre) and the Workshop Organizer (Dr. L. A. Diehl). The remainder of the morning was devoted to presentations by Lewis scientists C. J. Marek, L. P. Cooper, E. J. Mularz, and G. M. Reck which covered all the main aspects of the premix/prevaporize combustion problem with special reference to SCERP plans and objectives. After this briefing the participants divided into four separate working groups, and the rest of the day was spent with each group addressing one of the following areas: lean combustion phenomena, fuel-air preparation (premixing and prevaporizing), autoignition and flashback, and cycle and performance constraints. The composition of these working groups, each of which contained a nonparticipating liaison/advisor provided by NASA, is given in appendix B.

On the second day the participants reassembled and each working group presented its views and recommendations through its spokesman/chairman. General discussion of the topic followed each presentation. The Chairman's summary led to further general discussion after which the workshop terminated with concluding remarks from the Chairman and the Organizer.

One aim of the workshop was to solicit the views of a broad spectrum of combustion experts on the NASA SCERP program, but the discussion on this topic tended to be more concerned with points of experimental detail than with questions of research policy. This was probably because the participants felt that the program was well constructed and that it addressed itself directly to the problems of premix/prevaporize combustors as currently envisioned. However, some general comments were made to the effect that NASA research efforts in this area should be directed mainly toward the fundamental aspects, since the results obtained thereby would have more basic significance and more widespread application. It was also suggested that the overall emphasis of the program should be shifted more toward Advanced Supersonic Technology (AST) engines and that technology development efforts should continue to be aimed at the attainment of low NO_x during operation at altitude cruise.

In the earliest discussions on the workshop objectives, it was recognized that the field of lean, premixed/prevaporized combustion is so broad and complex that neat compartmentalization into four separate topics was impossible. Thus, it was anticipated that the deliberations of the four working groups would involve some degree of overlap and this was, in fact, reflected in their recommendations. However, only delicate surgery was applied in editing the working group's recommendations because it was felt that some reiteration of the same point by groups concerned with quite different aspects of the overall problem would help to identify the most important problem areas.

The report comprises a brief outline of NASA activities in the SCERP program followed by the summarized views and recommendations of the working groups and the Chairman's closing remarks. It is hoped that by focussing attention on important problem areas and by indicating gaps in current technology and expertise in premixed/prevaporized combustion the report will be of interest and guidance to all those agencies in government and industry who are responsible for formulating future policy in regard to research and development

of premix/prevaporize combustors for aircraft applications.

In conclusion, the Chairman would like to thank all the representatives from the universities, industry, and Lewis personnel for their attendance and active participation, and especially Professors M. Gerstein, A. Mellor, A. M. Faeth, and Dr. D. Bahr, who performed their roles as spokesmen/chairmen of the working groups in a most professional and able manner. Also worthy of special mention is Dr. L. A. Diehl of NASA Lewis for his contribution to the formulation of the workshop objectives and for the efficiency with which he attended to the needs of the visitors both before and during the meeting. The final word of thanks goes to NASA Lewis for sponsoring and hosting the workshop and for providing such excellent facilities.

A. H. Lefebvre
Purdue University
Workshop Chairman

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LEAN PREMIXED/PREVAPORIZED COMBUSTION

Workshop

NASA Lewis Research Center

Cleveland, Ohio

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PROBLEM STATEMENT

Although the impact of aircraft emissions on the total atmospheric pollution problem is small, its relative contribution is likely to increase in magnitude as a result of the legislation established for emission control on highway vehicles. Moreover, because much of the pollution from aeroengines is generated in and around airports, high local concentrations are attained. These low-level pollution effects have been well measured and documented, but in recent years there has been growing concern with the exhaust emissions produced by aircraft flying at high altitudes.

In the Climatic Impact Assessment Program (DOT, 1972-75), oxides of nitrogen, NO_x , were identified as a key pollutant emission during high-altitude cruise of both subsonic and supersonic aircraft; in its "Report of Findings," CIAP recommended six- to tenfold reductions in NO_x below current levels. Similar conclusions were reached by the Climatic Impact Committee (NAS, 1975) which recommended NO_x reductions from ten- to twentyfold during altitude cruise. In addition to meeting these formidable objectives, advanced technology engines must also comply with existing regulations promulgated by the EPA (Environmental Protection Agency) regarding pollutant emissions in the airport vicinity.

The magnitude of the problem is clearly brought out in figure 1 which shows typical NO_x emission levels for various types of combustors ranging from fully established, conventional burners to laboratory-type, premixed/prevaporized systems. Also shown, for comparison, are the target levels of NO_x . It is clear from this figure that the

required goals cannot be met with conventional combustors, and the system offering the most hope of success is the premix/prevaporize burner. However, it must be recognized that the very low NO_x emissions demonstrated by this system all relate to a fixed operating condition and considerable development will be required, embracing several detailed studies in certain basic areas, before the lean, premix/prevaporize concept (referred to henceforth as the LPP concept) can operate successfully over the entire range of flight conditions.

STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM

The previous considerations led to the formulation of a NASA program aimed at establishing and demonstrating the technology needed to reduce engine emissions to environmentally acceptable levels over the entire aircraft operating range with minimum adverse effects on performance, weight, and complexity. The specific goals are to achieve a six- to tenfold reduction in cruise NO_x below current levels and, at the same time, to meet or exceed the established EPA standards for the LTO (landing and takeoff) cycle. It is proposed to utilize in-house, contract, and university grant capabilities in the following four-phase activity:

Phase I - Fundamental Studies and Concept Assessment

Phase II - Concept Screening

Phase III - Experimental Combustor Development

Phase IV - Engine Verification

The work carried out so far has been confined to the early portion of Phase I. However, before discussing this in any detail, some reference should be made to the basic philosophy underlying the LPP concept.

It is generally agreed that NO_x is produced mainly by oxidation of atmospheric nitrogen in the regions of high temperature that exist within the reaction zone and around large burning droplets. A key feature of the LPP concept is the attainment of complete evaporation of the fuel and complete mixing of fuel and air prior to combustion. By avoiding

droplet combustion and by operating the combustion zone at a lean equivalence ratio, NO_x emissions are drastically reduced due to the low reaction temperature and the elimination of any "hot spots" in the combustion zone. In order to exploit its full potential, and to broaden its useful operating range, the LPP system should also feature some form of variable geometry.

The problems associated with the practical application of this concept include the following:

- Avoidance of blowout
- Premature autoignition
- Altitude relight
- Application of variable geometry
- Achieving satisfactory premixing and prevaporization
- Avoidance of autoignition and flashback
- Advanced control systems
- Impact of LPP burner on overall engine operation

PHASE I

The NASA plan for Phase I is illustrated schematically in figure 2. The four main areas shown on the left side of this figure together comprise the fundamental studies portion of the total Phase I activity. They include lean combustion, fuel-air preparation, autoignition and flashback, and cycle and performance constraints. These four elements of Phase I are now reviewed.

Lean Combustion

The main objective is to examine the factors influencing the performance and emission characteristics of LPP combustors. These factors include operating conditions (P , T , and ϕ), residence time, reference velocity, combustor geometry, and level of turbulence.

Some progress has already been made. For example, figure 3 is based on experimental data obtained from an LPP system and illustrates that NO_x emissions may be lowered by reductions in equivalence ratio and/or residence time while maintaining high levels of combustion efficiency. Another useful finding is that in many important respects the combustion characteristics of propane are very similar to those of Jet A kerosene. For example, the NO_x emissions are comparable, as illustrated in figure 4, and the carbon monoxide and unburned hydrocarbons emissions are similar. The lean blowout limits also agree closely. Thus, for many research purposes propane may be used as a convenient substitute for Jet A fuel. However, it should be noted that propane is generally less susceptible to autoignition than kerosene.

The influence of turbulence on emissions is illustrated in figure 5. Although no firm conclusions can be drawn from the modest amount of available data, it is clear from this figure that an increase in turbulence is beneficial from an emissions viewpoint, especially in regard to CO. However, it should be remembered that in practice any increase in the turbulence level is usually gained at the expense of some increase in the liner pressure drop.

Grants to promote further work in the area of lean combustion have been awarded to the University of California (Berkeley), Cornell University, and MIT. Contract research at GASL has already yielded some interesting results on the influence of pressure on NO_x emissions (see fig. 6) and a comprehensive series of tests, embracing wide ranges of pressure, temperature, and equivalence ratio is planned, based on the test rig shown diagrammatically in figure 7. The test program will include a series of improvements designed to elucidate the influence of flameholder geometry on emissions. Perforated plates, multiple cones, large cones, swirlers, multiple swirlers, and grids will be among the configurations tested.

In-house studies will include a number of experiments to be carried out at several levels of pressure, temperature, and equivalence ratio, using Jet A fuel, to determine the influence on emissions of flameholder

blockage and reference velocity. The test rig for these experiments is illustrated in figure 8.

Fuel-Air Preparation

A basic requirement is to supply the combustion zone with a homogeneous mixture of air and fuel vapor over a wide range of engine operating conditions. Unfortunately, accurate predictions of various important parameters such as spray angle, drop-size distributions, degree of vaporization, and uniformity of fuel-air mixing cannot yet be made. Moreover, the impact of these parameters on NO_x formation is unknown.

It is proposed to inject fuel into a flowing airstream and to investigate the effects of air flow parameters such as pressure, temperature, velocity profile, turbulence, and swirl on fuel atomization, spray penetration, droplet evaporation, and fuel dispersion as illustrated in figure 9. Various types of fuel and fuel injectors will be employed - the main objective being to achieve accurate prediction of fuel-air distribution, degree of fuel vaporization, and drop-size distribution as functions of the distance from the fuel injection point. An extension of this program will be to establish a fuel preparation model and then to carry out a series of verification tests as indicated in figure 10.

It is realized that a fully premixed and fully vaporized mixture may be attainable only over part of the engine operating range. It is intended, therefore, to examine the effects of incomplete fuel-air mixing and fuel evaporation on NO_x formation using the test rig illustrated in figure 11. Jet A fuel will be injected into the air flow at various distances upstream of a perforated plate flameholder. Probes located at the exit of the combustion zone will be used to measure the level of NO_x emissions and to indicate the extent to which these emissions are modified by changes in the degree of fuel vaporization, uniformity of fuel-air mixing, and drop-size distribution. Fuel drop sizes and drop-

size distribution will be measured using a light-scattering technique, as illustrated in figure 12.

Autoignition and Flashback

An intrinsic feature of the LPP concept is a tendency towards autoignition and flashback. Thus, before the system can be applied with confidence to a modern high pressure ratio engine, the flame stability and spontaneous ignition characteristics of premixed fuel-air mixtures must be properly understood.

In-house activities in this area include studies of hot surface effects on autoignition and the role of the boundary layer in the phenomenon of flashback. The objectives of the former are to study the autoignition characteristics of a prevaporized fuel-air mixture when flowing along a wall which is at a different temperature. It is proposed to locate various test plates (2-D and axisymmetric) in a premixed flow whose pressure and temperature can be varied up to 25 atmospheres and 813 K, respectively. Provision will be made for independent control of the surface temperature above or below the gas temperature. The presence of flame will be indicated by skin thermocouples and silicon photovoltaic detectors. The experimental data obtained from the investigation will be plotted in the form of autoignition limits as a function of gas temperature, pressure, velocity, composition, and test plate temperature.

Similar test plates (2-D and axisymmetric) immersed in a premixed flow will be used to study flashback characteristics in the boundary layer. The test conditions will include gas pressures up to 25 atmospheres, gas temperatures up to 813 K, and various levels of turbulence. It is proposed to stabilize a flame in the wake of the test plate and then to adjust the flow conditions until flashback occurs. The onset of flashback will be observed visually through quartz windows in the tube, supplemented by silicon photovoltaic detectors. The purpose of the investigation is to determine flashback limits as a function of mixture composition and flow conditions. The effects of various

boundary layer modifications (e.g., trips) will also be examined.

Contract research on autoignition includes a program (NAS3-20066) for developing a critical experiment to determine the autoignition characteristics of aircraft-type fuels at elevated temperatures and pressures. It is intended to carry out general studies on the effects of physical and chemical properties of fuels, at pressures up to 30 atmospheres and temperatures up to 900 K, and also to obtain detailed information on the autoignition characteristics of ASTM Jet A and JP-4 fuels.

Engine Constraints

This aspect of the program is concerned with the combustor environment and the constraints imposed on the combustion system through interface with the engine. The problems envisioned are summarized in figure 13. A major consideration is, of course, the very wide range of combustor inlet conditions exhibited by advanced turbojet engines, as illustrated in figures 14 and 15. An important related problem is the marked variation in compressor discharge characteristics (velocity profile, turbulence properties, etc.) that often occur with changes in power setting, as illustrated in figure 16. Studies are underway to determine the turbulence characteristics of the compressor efflux for some typical current engines over a wide range of operating conditions. The measurements will include mean velocity, turbulence intensity, turbulence scales, frequency probability, and velocity probability distributions. The objective is to correlate all the important turbulence characteristics with engine power level.

Another significant factor is the wide variation in flame zone equivalence ratio that occurs with changes in engine operating conditions, as illustrated in figure 17. The corresponding variations in flame temperature are incompatible with low emissions. Thus, figure 17 underlines the need for variable geometry to control the flame-zone equivalence ratio and hence also the flame temperature.

PHASES II, III, AND IV

As the results of the Phase I studies become available, the design data will be applied to combustor concepts. In Phase II a number of variations of each concept will be experimentally screened to identify the most promising. These designs will then be further developed in Phase III to optimize off-design performance, ignition, liner wall cooling, altitude relight performance, etc. The best design will be selected for full-scale engine verification in Phase IV. It is anticipated that Phases II, III, and IV will be contracted efforts with the engine manufacturers.

WORKING GROUP DISCUSSIONS

LEAN COMBUSTION PHENOMENA

A basic tenet of the LPP concept is the attainment of low temperature throughout the combustion zone. This implies that over a large portion of the engine operating range the equivalence ratio in this zone must, of necessity, lie close to the weak extinction value. Unfortunately, very little is known about the performance and behavior of practical combustion systems operating at very low equivalence ratios. It is a region which is usually avoided, partly from a desire to attain the higher burning rates associated with richer mixtures, but also to minimize the risk of flame extinction. The experience gained on afterburner systems, which are also designed to operate with fairly lean prevaporized fuel-air mixtures, would appear to indicate that combustion instability could prove to be a serious problem.

In its deliberations on lean combustion phenomena, the working group gave special consideration to engine cycle parameters, such as combustor inlet air pressure and temperature, and to the effects of spray characteristics, degree of fuel evaporation, and flameholder geometry. Various possible methods of extending the weak extinction

limits and/or promoting combustion under lean conditions were also discussed.

Following its discussions, the working group on lean combustion phenomena presented its findings in the form of the following recommendations (see appendix B for working group assignment):

(1) In view of the complexity of the phenomena, and the changing requirements arising from developments in engine technology, it is recommended that both lean combustion and exhaust gas modification be examined as methods of reducing NO_x . Exhaust gas modification (i. e., removal of NO_x formed in the primary combustion process) could prove especially beneficial where high turbine inlet temperatures are required or where fuels containing appreciable nitrogen must be used.

(2) The tolerance of lean combustion to variations in combustor inlet flow conditions should be examined. The role of the diffuser in amplifying or damping flow nonuniformities and pressure pulsations should also be considered.

If these effects are found to be significant, it would indicate that potential improvements could stem from design modifications to the compressor and/or diffuser. Another useful approach would be to investigate the effects of turbulence promoters and other control devices located upstream of the flameholder in helping to achieve a more uniform and stable flow of air into the combustion zone.

(3) It is recommended that, in addition to variable-geometry flameholders or liners which are intended primarily to control and regulate the distribution of air throughout the chamber, consideration should be given to methods of achieving low combustion temperatures by "staging" the injection of fuel. This may necessitate more complex fuel injector and flameholder designs that have hitherto been contemplated. Studies should also be made to determine the optimum location for the fuel injectors in such multistage combustion systems.

(4) A fundamental investigation should be conducted to determine the influence of all the relevant parameters on weak extinction limits.

The combustor configuration employed in this investigation should incorporate all the characteristic features of a practical combustion system. The variables investigated should include air pressure, air temperature, reference velocity, turbulence properties, humidity, and fuel type.

(5) Methods of artificially extending the extinction limits by "pilot" flames should be examined. Piloting action could be obtained in many ways, ranging from a simple swirl atomizer through stratified charge injectors to fairly sophisticated catalytic combustion devices. In any case, the NO_x forming tendencies of the pilot should be examined since, to be fully effective, the pilot flame must run hotter than the main combustion process; consequently, its potential for NO_x formation is relatively high. The experimental program should also include a study of "glow plugs" of the type that have proved successful in relighting the flame after extinctions caused by the ingestion of water or ice.

(6) Experiments should be conducted to determine the extent to which departures from perfect homogeneity (in terms of fuel vaporization and fuel-air mixing) the combustion process can tolerate without any appreciable increase in NO_x emissions. A related problem is the sensitivity of the system to transient departures from ideal conditions such as occur, for example, during engine acceleration and deceleration.

(7) Methods for accelerating or promoting fuel evaporation should be investigated. The study should include consideration of fuel additives, fuel preheating, and supercritical fuel systems.

The influence of dissolved air in the fuel on the subsequent evaporation processes should also be examined. The use of heat recirculation to promote fuel evaporation and improve stability is another interesting possibility that should be explored.

(8) The similarities that exist between the LPP concept and the combustion systems employed in conventional ramjets and afterburners give rise to concern in regard to combustion oscillations. This aspect warrants more detailed analytical and experimental investigation.

(9) It is strongly recommended that, in order to derive the maximum benefit from the proposed experiments, complimentary programs of analysis and mathematical modelling should be undertaken. It is believed that a firm theoretical foundation will appreciably reduce the time and cost of experimentation and add much to the significance of the results obtained.

FUEL-AIR PREPARATION

It is now well established that the presence of liquid fuel drops in the combustion zone, combined with local imperfections in fuel-air mixing, is conducive to the formation of NO_x , unburned hydrocarbons, and smoke.

Thus, a basic requirement of the LPP concept is that the fuel should be completely vaporized and uniformly mixed with all the air which subsequently participates in combustion. This principle is by no means novel as far as the aircraft gas turbine is concerned, since most conventional afterburners are designed to operate with a fully evaporated and fairly homogeneous fuel-air mixture. However, the afterburner situation is greatly simplified by the almost ideal temperature of the turbine efflux gases. These gases are usually hot enough to evaporate the injected fuel within a relatively short distance, but are not so hot so as to create problems of autoignition and flashback. Moreover, the afterburner system is not normally required to operate near the weak extinction limit - in fact, fuel staging is frequently employed to ensure that it does not. Thus, the experience gained on afterburner systems unfortunately makes little or no contribution to the problems involved in the application of the LPP concept to the main combustor.

After a full discussion of all the foreseeable problems, the working group identified a number of research recommendations:

(1) Measurements should be carried out to determine the turbulence properties of the compressor discharge air. The role of the diffuser in modifying these turbulence characteristics should also be examined.

(2) Experiments should be designed to evaluate the separate effects of turbulence intensity and turbulence scale on fuel vaporization and fuel dispersion.

(3) Since pressure loss is usually incurred in the generation of turbulence, efforts should be made to establish the trade-off between liner pressure drop and lean blowoff limits.

(4) The experimental program outlined in (2) should also include variations of fuel type, fuel temperature, and fuel injection method.

(5) Transfer numbers for calculating fuel evaporation rates should be determined experimentally over a wide range of operating conditions. Data of this type are needed especially for the new and complex fuels now being considered for gas turbine applications.

(6) The extent to which propane may be used to provide an accurate simulation of conventional liquid fuels should be more firmly established. More detailed information on this aspect would simplify experimentation and enhance the relevance and authenticity of experimental data obtained with propane fuel.

(7) The relative merits of airblast, air-assist, and pressure atomizers should be critically examined in regard to fineness of atomization and drop-size distribution. Since the atomizing characteristics of these three types of injector vary appreciably with ambient pressure, the experimental program should include comparative tests carried out over a wide range of pressures.

(8) Droplet evaporation studies should be conducted over a range of air pressures and temperatures to establish the relations between fuel drop size and evaporation time (or distance).

AUTOIGNITION AND FLASHBACK

Perhaps the most formidable obstacles to the successful development of the LPP concept are the problems of autoignition and flashback. Detailed information on the steps necessary to avoid these phenomena are an essential prerequisite to the screening of potential design con-

cepts. Since these concepts are poorly defined at this point, fairly fundamental studies are desirable so that the results can be applied to a variety of systems.

The working group's discussions were divided between the two main areas of autoignition and flashback with the objective of defining the critical investigations needed to provide fundamental information in these areas prior to defining specific concepts. To avoid confusion, the operational definitions of flashback and autoignition were chosen as follows:

Flashback - Fast chemical reaction, accompanied by significant heat release, in the premix/prevaporize section of the combustor due to upstream propagation of a flame from the active combustion section

Autoignition - Fast chemical reaction, accompanied by significant heat release, in the premix/prevaporize section of the combustor arising from any source other than flashback

The results of either event is the same - namely, the flame leaves its intended point of attachment to the flameholder and is located for some period of time within the premix/prevaporize section. This action leads to potential damage or shortened life of combustor components, as well as loss of desirable emission characteristics due to failure to achieve the designed premixing levels.

The working group also adopted the following definition for ignition delay:

Ignition delay - Time interval between the fuel and air coming into contact and the point where fast chemical reaction, accompanied by appreciable heat release, is observed

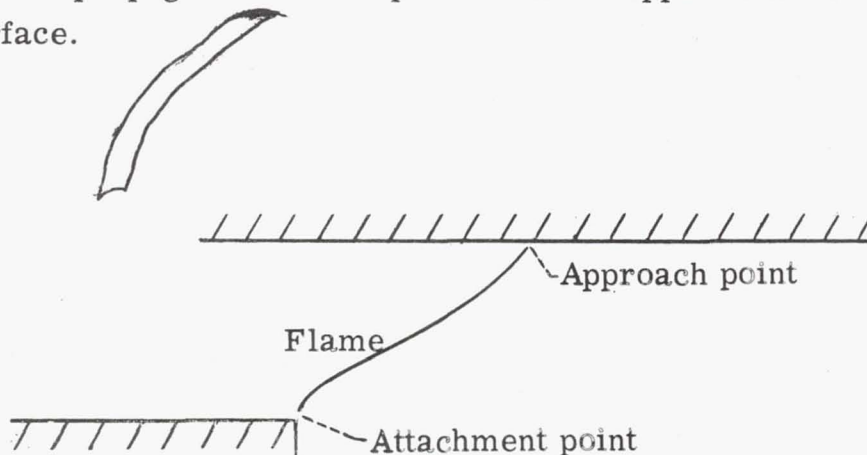
Flashback

Two major types of flashback were identified: (1) flashback occurring in the free stream, and (2) flashback occurring through the low velocity flow in the boundary layer along the surfaces of the flame-

holder, any support struts, and the walls of the premix/prevaporize section. Either mechanism may involve homogeneous and/or heterogeneous reactions.

The most obvious free stream mechanism would involve flashback due to a flow reversal in the bulk flow through the combustor. This flow reversal could be a result of compressor surge, a large disturbance due to a foreign object passing through the engine, or combustion instability. Flashback can also occur in the absence of flow reversal if the turbulent flame speed through the gas in the premix/prevaporize section is greater than the local bulk velocity. While lean combustion tends to reduce flame speeds, other factors associated with the engine cycle, such as high temperatures, pressures, and turbulence levels and preignition reactions in the gas due to appreciable residence times at high temperature levels, cause increased flame speed. Therefore, there is some concern that flame speeds may be sufficiently high to increase the minimum allowable velocity in the premix/prevaporize section to unacceptable levels in order to avoid anticipated disturbances of the combustion process. Therefore, flame speed information is necessary to specify allowable tolerances on levels of flow disturbance and minimum velocities.

The boundary layer mechanism involves flashback through the retarded flow in a boundary layer. Two geometrical configurations can be envisioned as shown in the sketch: Forward propagation from the point of attachment of the flame along the surface of a flameholder, and forward propagation from a point where it approaches or impinges on a surface.



Important parameters that were identified involve the following:

- (1) Surface conditions - Wall temperature and temperature distribution, geometrical configuration
- (2) Boundary layer - Structure, turbulence, thickness, ambient pressure gradient, etc.
- (3) Free stream conditions - Temperature, pressure, mixture ratio, residence time in the mixing vaporizing section, etc.

Control of this phenomenon can be approached by controlling wall temperatures, reducing equivalence ratios near surfaces, and reducing the width of retarded zones by applying a free stream pressure gradient, etc.

Autoignition

Homogeneous and heterogeneous mechanisms can also be identified for autoignition. The homogeneous mechanism involves a parcel of fuel-air mixture having an excessive residence time in its passage through the premix/prevaporize section. If the ignition delay time is exceeded, autoignition occurs prior to the mixture reaching the flameholder. Reduction of residence time to avoid this problem can be approached in a number of ways:

(1) Reduce residence time requirements by preheating or prevaporizing the fuel in the absence of air; in this manner only uniform mixing requirements must be met and design flexibility is obtained by controlling the number of fuel injector locations at the inlet of the mixing section.

(2) Reduce residence time and accept potentially larger emission levels due to inhomogeneous fuel concentrations and the presence of droplets at the entrance of the combustor under some conditions.

Two heterogeneous autoignition mechanisms were identified:

(1) Local free stream hot spots - Abrasion of compressor components is a technique which is currently employed to provide good seals within the compressor. Abraded particles leaving the com-

pressor are potential ignition sites if they contain sufficient ignition energy when they reach regions of combustible mixture.

(2) Wall ignition - Excessive wall temperature levels in the premix/prevaporize section could also cause autoignition. If this occurs from the combustor end, it is related to flashback. If it occurs elsewhere due to higher wall temperatures than free stream temperatures as a result of vaporization induced cooling of the free stream, it would constitute autoignition as defined here. This problem can be controlled by proper thermal management of wall temperatures or by varying the mixture ratios near the wall.

Recommendations

Flashback

First, experiments should be conducted to evaluate flame attachment and stability for conditions representative of the downstream end of the premix/prevaporize section. In addition, propagation through the boundary layer as the flame approaches an adjacent surface should also be evaluated. The following factors should be studied:

- (1) Free stream conditions - Pressure, temperature, velocity, premix/prevaporize section residence time, turbulence level
- (2) Wall conditions - Effect of wall temperature and wall temperature distribution in the region upstream of the point of attachment
- (3) Boundary layer - Effect of boundary layer structure, thickness, lengthwise pressure gradient and pressure disturbances

In the early stages of this study it would be desirable to evaluate a number of these factors in a relatively large-scale, well-controlled, experiment at atmospheric pressure. This would be followed by testing at pressures more representative of actual operating conditions, once the important factors involved in specifying a well-defined experiment have been evaluated. Critical areas identified in the initial ex-

periments should also be examined by more detailed measurements, e.g., the point of attachment.

Fuel types representative of the application should be examined early in the study. A uniform mixture should be employed in the early stages of the work in order to control test variables; nonhomogeneous mixtures or mixtures containing droplets should also be examined.

The experiments should also be supported by a modelling effort, in order to provide a basis for data correlation and interpretation of the results. The literature of boundary layer flame propagation should also be examined.

Second, the status of available information on flame speeds under conditions representative of the premix/prevaporize section should be evaluated. This should include representative fuel types, turbulence levels, temperatures, pressures, mixture ratios, nonhomogeneous mixtures, and residence time. Where gaps in information are found, appropriate experiments should be undertaken to provide this fundamental information.

Third, it is not clear to what extent effort is being devoted to characterizing expected levels of flow disturbances. Experimentation on flashback should consider expected disturbance levels, and this aspect of the problem also deserves attention.

Autoignition

First, a review of the extensive literature on autoignition should be undertaken that considers conditions representative of this application: temperature, fuel type, pressure, turbulence level, presence of drops or mixture inhomogeneity, etc.

Second, in the absence of reliable available data, experiments should be undertaken to determine ignition delays under completely premixed conditions, i.e., in the absence of vaporization and turbulent mixing delays. This information would provide a well-defined baseline

for subsequent work to aid in the evaluation of vaporization and non-homogeneous mixtures on autoignition.

Third, at the other end of the spectrum, ignition delays should be measured for droplets, using representative fuels and drop sizes representative of the larger sizes from anticipated injectors. This would provide baseline information on heterogeneous ignition phenomena.

Fourth, experiments should be undertaken to determine homogeneous ignition delays under conditions representative of the premix/prevaporize section. The fuel types should also be representative; however, preheating/prevaporizing the fuel might be considered in the early stages so that mixing effects would be dominant. The experiments should be controlled so that representative turbulence levels, spray characteristics, and mixing nonhomogeneities could be evaluated along with such factors as approach temperature and pressure and wall boundary conditions.

Fifth, potential problems arising from injection of abraided particles into the combustor from the compressor should be evaluated.

Final Observations

Although flashback and autoignition are difficult theoretical problems, analysis is recommended since even very simplified models would be helpful in planning experiments, providing proper experimental controls, and interpreting data.

Also, the proposed combustion system is similar in many respects to an afterburner. This suggests that problems may be encountered with rough or unstable combustion. Occurrences of this type could have an important bearing on flashback in the present system; therefore, designs should be evaluated for potential instability problems.

CYCLE AND PERFORMANCE CONSTRAINTS

At the outset of its discussions on this aspect of Phase I, the working group noted that, as presently planned, the SCERP program emphasizes the development of LPP combustors for subsonic transport engine applications, including the attainment of low NO_x at take-off conditions. However, in view of the very severe combustor operating conditions of advanced subsonic engines ($T_3 > 800 \text{ K}$, $P_3 > 30 \text{ atms}$, overall equivalence ratio > 0.35), it was felt that attempts to obtain uniform and well-vaporized fuel-air mixtures at these extreme conditions could seriously inhibit combustor development. The working group questioned the need for ultra-low NO_x emissions at takeoff, and also at cruise in the case of subsonic engines.

Part of the working group's assignment was to examine the impact of LPP combustion on ignition, stability, liner wall cooling, and temperature traverse quality. The main points of discussion and the conclusions drawn are summarized in the following sections.

For satisfactory lightup on the ground and adequate altitude re-light and idle performance, it was felt that a "starting" combustor of fairly conventional design should be incorporated into the combustion chamber along with the LPP system. Ideally, the LPP system should be capable of operating at all flight conditions without the starting combustor stage (or zone). It is, of course, essential that the LPP system should operate without support from the starting combustor at cruise, if low NO_x is to be obtained.

A smooth transition between the starting combustor and the LPP system, within the established time limits for acceleration from idle to full power, is required. Also, during deceleration to idle, provision should be made for rapid lightup of the starting combustor.

Precise synchronization of the starting combustor fuel flow and the LPP combustor fuel flow is necessary. An added complication is the need to purge the starting combustor fuel injectors after shutdown.

In order to achieve stable operation of the combustion zone at equivalence ratios near the weak extinction limit, it is essential that the compressor outlet airflow pattern should be steady and uniform. However, the limited amount of available evidence suggests that the circumferential velocity distribution of current compressors is far from uniform. The problem is further aggravated by distortions of the compressor inlet airflow pattern due to aircraft installation features and other causes. Thus, some improvements over current compressor design technology may be needed to eliminate or minimize this problem.

New technological advances are also required in the area of liner wall cooling. Due to the very large increase in combustion air demanded by the LPP concept, the amount of air available for wall cooling is correspondingly much less. To some extent the problem can be eased by selecting an annular liner. Compared with can-annular systems, the annular configuration has distinct advantages in terms of shorter length and lower surface to volume ratio. Incidentally, the annular type of combustor should also exhibit better ignition and stability performance due to continuous circumferential flame propagation around the annular liner, as opposed to the can-annular system in which the circumferential passage of flame and hot combustion products can only proceed through crossfire tubes of relatively low cross-sectional area.

In order to provide acceptable temperature profiles at the turbine inlet, some provision must be made for introducing dilution air at the downstream end of the liner. However, this dilution air can only be obtained at the expense of a reduction in combustion air, and this could limit the lowest obtainable value of combustion zone equivalence ratio, especially when the overall equivalence ratio is high. To deal effectively with this problem, more information is needed on how dilution zones behave when both the inlet gas temperature and the quantity of dilution are low.

To maintain low NO_x over the required range of flight conditions, i. e., at all operating conditions above idle, continuous modulation of the air flow entering the combustion zone is imperative. The basic problem is one of arranging for the combustion equivalence ratio to be always close enough to the weak extinction limit for the NO_x emissions to be acceptably low, but not so close as to cause flame extinction during a transient engine airflow excursion. Some form of variable geometry to regulate and control the amount of air entering the combustion zone is clearly required. However, some additional coordinated variable geometry is called for in order to vary the amounts of air employed in liner wall cooling and dilution so as to maintain a constant liner pressure drop. These complex variable geometry provisions will require fairly sophisticated digital control systems, including appropriate sensors, to maintain a near-constant equivalence ratio in the combustion zone over a wide range of flight conditions.

A further problem arising from the use of variable geometry is that in order to obtain suitably low residence times at cruise conditions the residence times at other flight conditions may be too short for adequate mixing and fuel vaporization.

The working group's recommendations for dealing with these cycle and performance constraints are now summarized:

(1) SCERP technology development efforts should continue to be focussed primarily on obtaining low NO_x emissions at cruise (and especially AST engine cruise) operating conditions.

(2) Consideration should be given to moving the overall emphasis of the program more toward AST engines and away from subsonic transport engines.

(3) It would be worthwhile to evaluate the autoignition and flashback characteristics of LPP combustor concepts, particularly at take-off conditions.

(4) Studies should be initiated to determine appropriate starting combustor concepts. These studies should include an assessment of the range of engine starting conditions over which the starting combustor would be required. The impact of the starting combustor on

the overall NO_x emissions should also be examined.

(5) Appropriate means for lighting, relighting, controlling, and purging the starting combustor should be investigated.

(6) More data on compressor discharge airflow characteristics, including turbulence properties, should be sought. If, as expected, appreciable variations in radial and circumferential velocity profiles are found, then research should be initiated to establish appropriate compressor design technology for achieving a more uniform compressor efflux.

(7) The various recent developments in liner wall cooling should be critically reviewed and assessed for their application to LPP combustors. Estimates should then be made of the quantities of cooling air required by these new methods in their application to AST and subsonic transport engines.

(8) Research aimed at establishing design rules for LPP dilution zones of minimum length should be initiated. The main objective is to extend conventional dilution-zone design technology to include lower inlet gas temperatures and smaller proportions of dilution air than have hitherto been contemplated.

(9) The application of variable geometry devices for regulating and controlling the admission of air through the various liner ports should be studied in detail. Both mechanical design features and electrical control aspects should be investigated. Since the use of variable geometry will probably incur some departures from the baseline liner pressure drop, the influence of liner pressure drop on all important aspects of combustion performance should be determined.

(10) Experiments should be conducted to ascertain the NO_x levels near the weak extinction limits in order to establish adequate lean blowout margins.

(11) Methods of external fuel heating to promote flash vaporization should be studied as well as a means for suppressing carbon formation on hot metal surfaces.

(12) The additional impacts and constraints associated with the possible use of LPP combustion in business jet aircraft engines should be evaluated.

CHAIRMAN'S CONCLUDING REMARKS

I will not attempt to summarize all the viewpoints expressed during the 2-day conference but will confine my observations to those aspects of the lean, premix/prevaporize concept which strike me as being the most important. The first problem is in knowing where to start; perhaps the compressor exit would be the most logical place. It seems very clear that the success or otherwise of the LPP concept will depend to a large extent on the ability of the combustion zone to function satisfactorily at equivalence ratios near the weak extinction limit over much of the engine operating range. Even if the combustor inlet flow were perfectly stable or uniform, this would present a formidable design goal. However, what little data exist suggest that compressor outlet conditions are far from uniform and that appreciable differences occur in velocity profile, angle of swirl, etc., between compressors of ostensibly the same design and even with any given compressor at different flight conditions. Moreover, measurements have indicated that even when a compressor is operating stably at its design point appreciable circumferential variations in outlet flow pattern can occur. If one adds to all this the problem of compressor inlet flow distortion, then it is very clear that substantial difficulties may occur in integrating the LPP concept with the compressor.

Another source of flow distortion and instability is the diffuser. Perhaps we need to reconsider its role. Hitherto diffuser design has focussed on achieving a given velocity reduction with the minimum loss of total pressure and in the shortest possible length. Perhaps we should now examine the potential of the diffuser for attenuating flow instabilities and velocity maldistributions in the compressor efflux.

The various schemes proposed for preheating the fuel seem superficially attractive, but one must remember that the quality of aircraft fuels is more likely to deteriorate than improve; consequently, thermal decomposition could pose a serious problem.

At the present time the most practical means of achieving rapid fuel evaporation would appear to be via ultrafine atomization. Analysis and experimentation should be pursued to determine the time or distance needed to fully evaporate the fuel as a function of air flow properties and fuel drop size. New approaches to fuel atomization aimed at the production of very small droplets should be explored. Allied to this is the problem of measurement of small drop sizes ($<20 \mu$). Every encouragement should be given to new ideas and the development of new techniques.

Transfer numbers for estimating fuel evaporation rates should be determined experimentally over a wide range of operating conditions for the alternative fuels now being considered for gas turbine use.

The toughest barriers to the practical realization of LPP combustion in advanced aircraft engines are the related problems of autoignition and flashback. As these problems and their potential solutions have been fully elucidated by the working group on this topic, I will not attempt to reiterate their views and recommendations which I thoroughly endorse. However, I would like to reinforce their plea for a comprehensive literature survey and for the maximum possible analytical effort and modelling support.

The LPP concept is based on supplying the combustion zone with a fully mixed and fully vaporized fuel-air mixture. Both these requirements may prove very difficult to obtain in practice, at least within reasonable lengths and without incurring autoignition and/or flashback. Thus, it would seem very desirable to determine the extent to which departures from perfect homogeneity (in terms of evaporated fuel-air mixing) affect the emissions of NO_x and other pollutants. A related question is how many fuel drops can the com-

bustion zone tolerate before it loses its homogeneous traits.

Reference has already been made to the possibility that LPP systems might prove especially prone to combustion instability. I share this concern. In general, improvements in fuel-air mixing prior to combustion usually encourage the onset of instability. Moreover, instability is often associated with combustion occurring near an extinction limit. The LPP system qualifies on both counts, which suggests that combustion instability could prove a serious stumbling block and therefore warrants thorough investigation.

I referred earlier to the problem of maintaining combustion over a wide range of flight conditions while operating close to the weak extinction limit. Even with advanced forms of variable geometry, used in conjunction with the most sophisticated digital control systems (which, incidentally, we do not yet have), the risk of "flame out" will always be present unless provision is made either to postpone extinction by supplementing the rate of heat generation at one or more local regions of the flame or to arrange for immediate re-ignition by means of, say, a glow plug.

Piloting action could be provided either by fitting a separate "starting" combustor or fairly conventional design, as advocated by the engine working group, or by arranging for some regions of the combustion zone to be either more lightly loaded than others or to operate at a slightly higher equivalence ratio. Here is a fruitful area for design ingenuity.

Another recommendation that emerged from most if not all of the working groups, and one which I fully support, is that analysis and modelling techniques should be applied whenever and wherever possible in all phases of the LPP combustor program. This would improve efficiency, reduce costs, and ensure that the results obtained and the lessons learned have useful applications far beyond the confines of the envisaged program.

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APPENDIX BWORKING GROUP ASSIGNMENTSLean Combustion Phenomena

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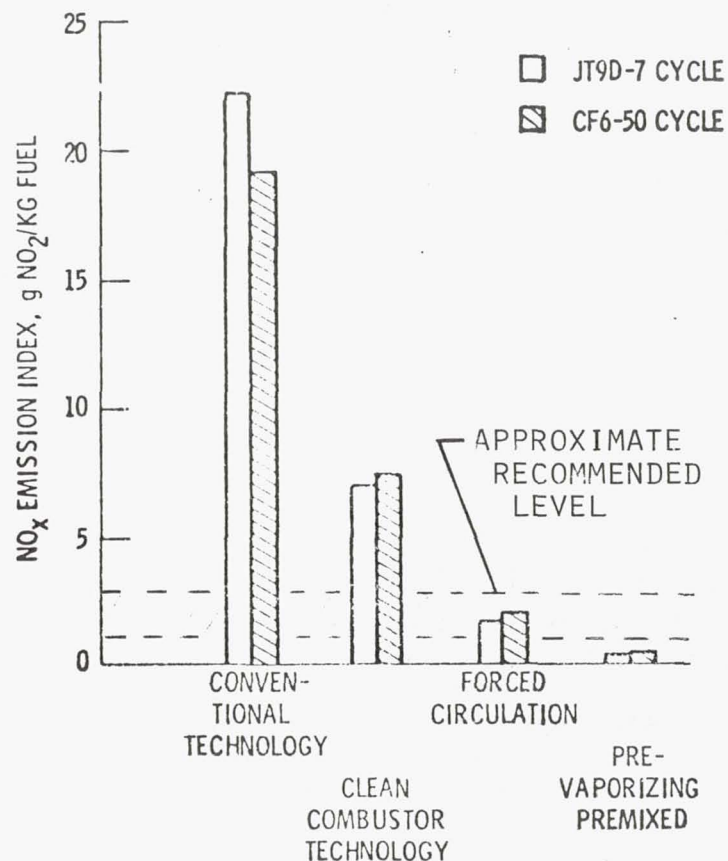
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(1) - Observer
(2) - NASA Lewis personnel



NO_x emissions forecast for subsonic cruise, Mach number = 0.85 at 10.7 km altitude.

- RECOMMENDED NO_x REDUCTIONS OF 6- TO 10-FOLD PRECLUDES THE USE OF CONVENTIONAL TECHNOLOGY
- LABORATORY TESTS OF PREMIXING, PRE-VAPORIZING BURNERS HAVE DEMONSTRATED THE RECOMMENDED REDUCTIONS AT FIXED CONDITIONS: HOWEVER, SUCCESSFUL APPLICATION OVER RANGE OF OPERATING CONDITIONS WILL REQUIRE ADVANCEMENT IN SEVERAL FUNDAMENTAL AREAS.

Figure 1. - Aircraft emissions reduction problem.

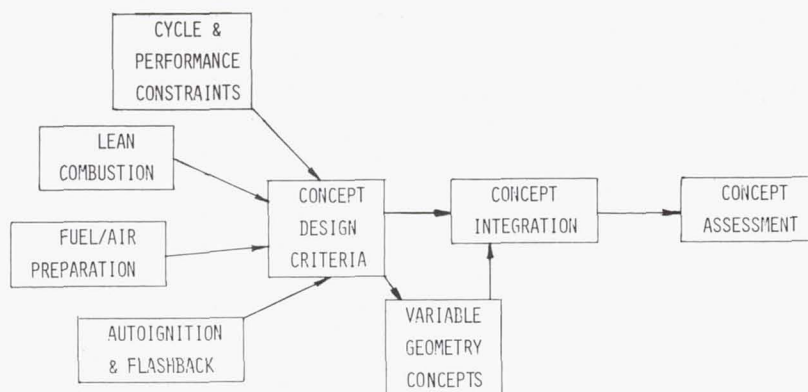


Figure 2. - Stratospheric cruise emission reduction concept assessment.

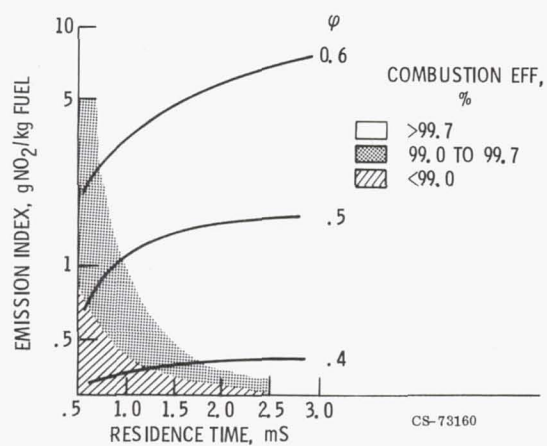


Figure 3. - Combustion efficiency and NO_x emissions.

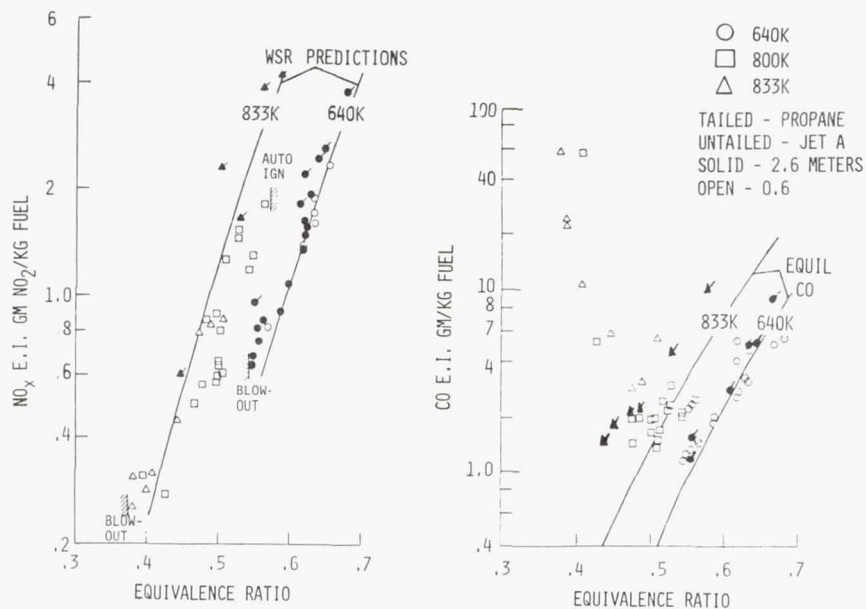


Figure 4. - Comparison of emissions for propane and jet-A fuel.

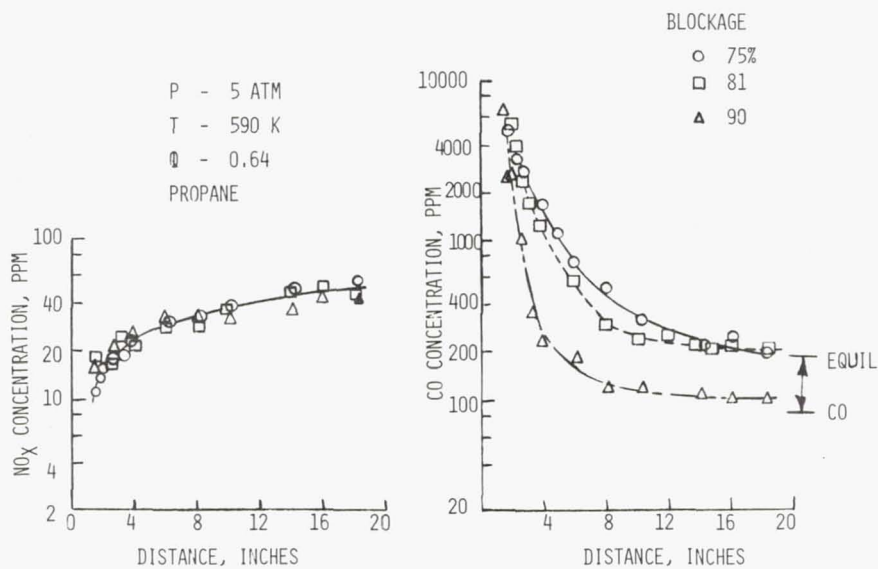


Figure 5. - Effect of turbulence on emissions.

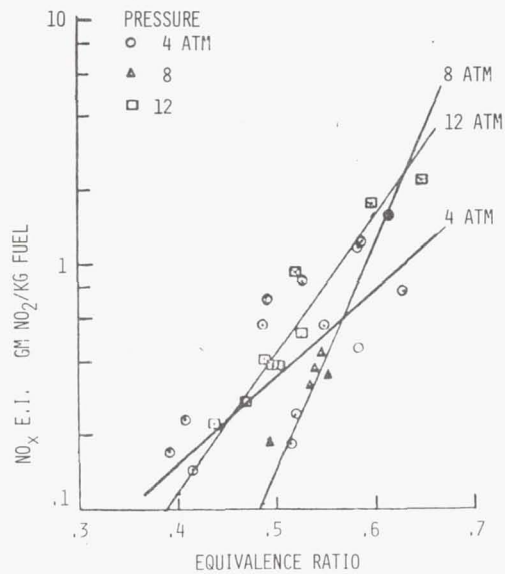


Figure 6. - Effect of pressure on NO_x emissions at 800 K.

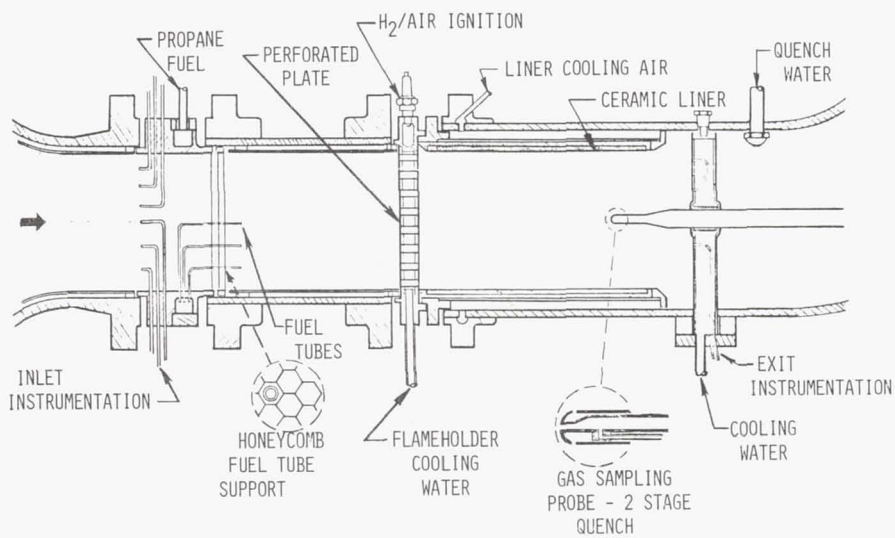
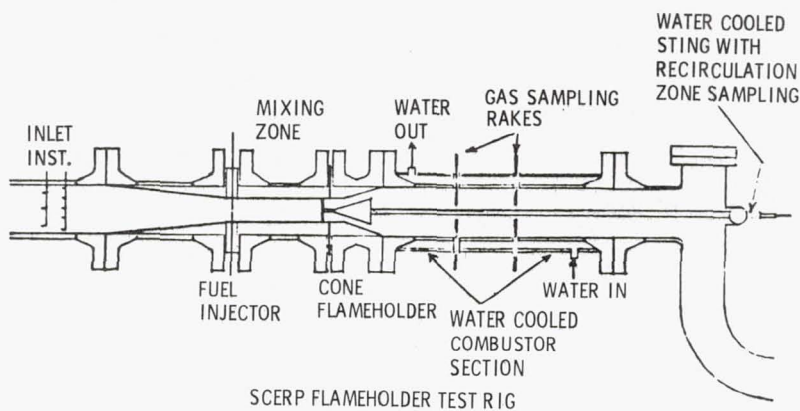


Figure 7. - High pressure emissions test rig (GASL).



TEST CONDITIONS:

P_3 (kPa) 100 - 500
 T_3 (K) 600 - 800
 ϕ LBO - 1.0
 JET A FUEL

Figure 8. - Flameholder geometry study (ORL-11).

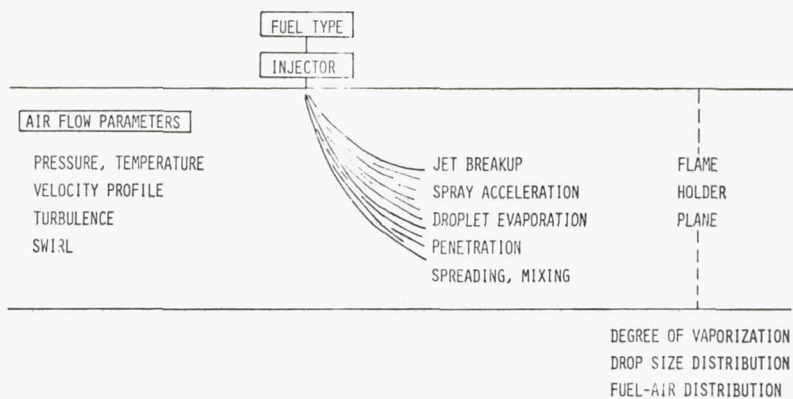
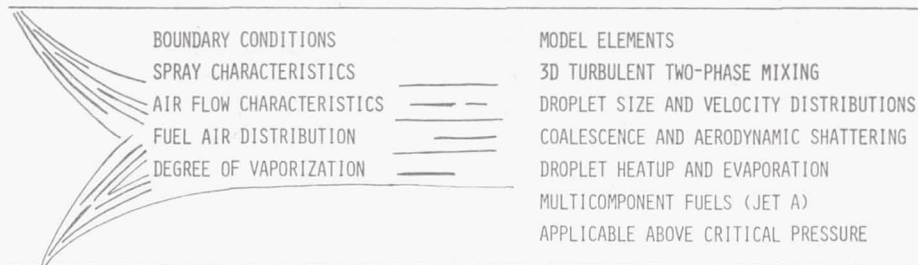


Figure 9. - Fuel preparation section.

GOAL: ACCURATE PREDICTION OF FUEL-AIR DISTRIBUTION, DEGREE OF VAPORIZATION, AND DROP SIZE DISTRIBUTION AS FUNCTION OF DISTANCE FROM INJECTION POINT



MODEL VERIFICATION

GOAL: MEASUREMENT OF BOUNDARY AND DOWNSTREAM CONDITIONS NECESSARY TO VERIFY FUEL PREPARATION MODEL

Figure 10. - Fuel preparation model.

EXPERIMENTAL CONDITIONS

TEMPERATURE, K	530 - 810
PRESSURE, atm	5
VELOCITY, m/sec	15 - 45
FUEL	JET A
ϕ	0.2 - 0.8

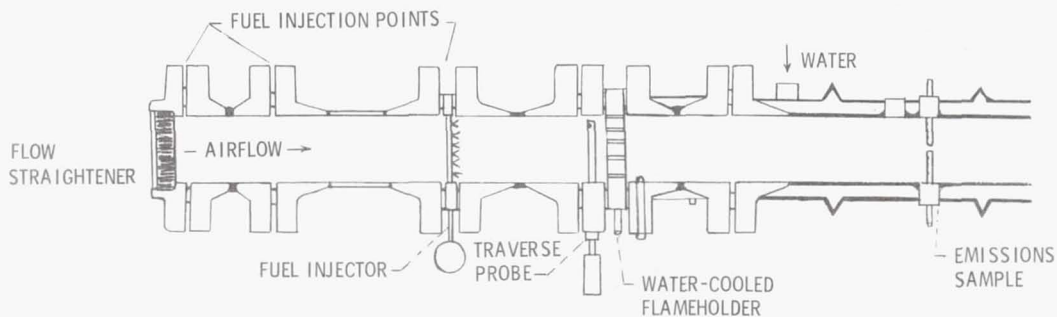


Figure 11. - Fuel preparation section.

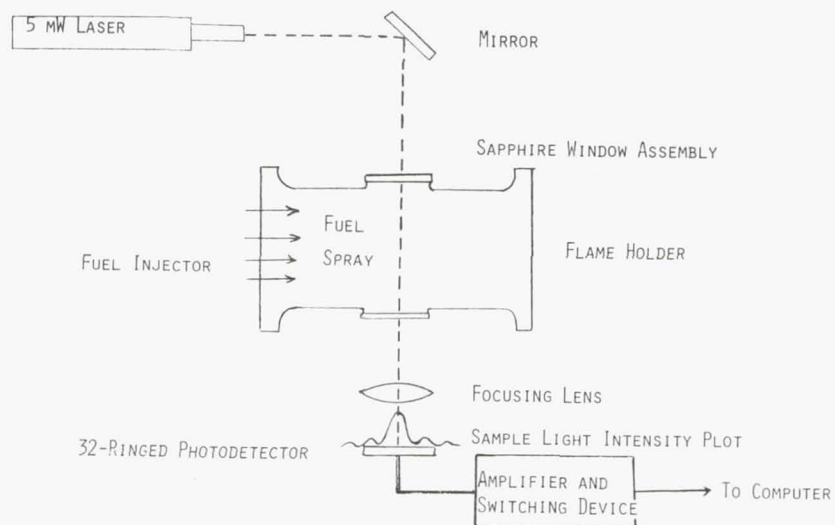


Figure 12. - Schematic of laser drop-size measurement system.

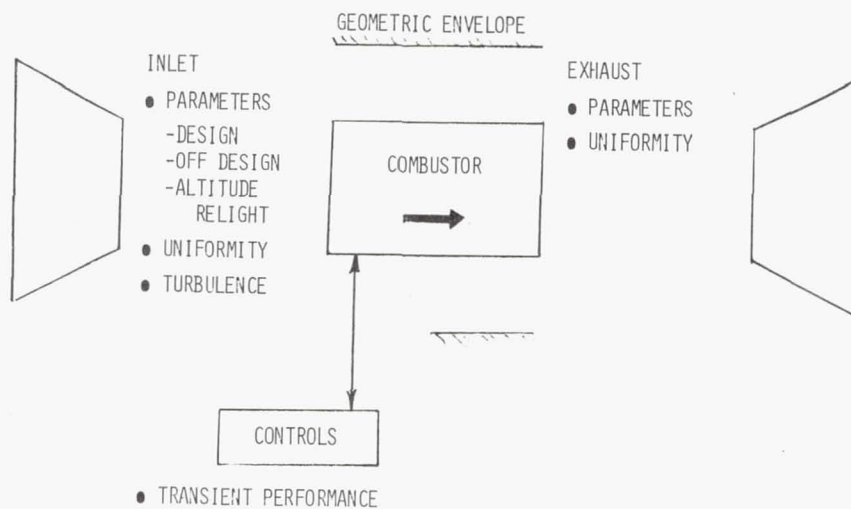


Figure 13. - Engine constraints - problem areas.

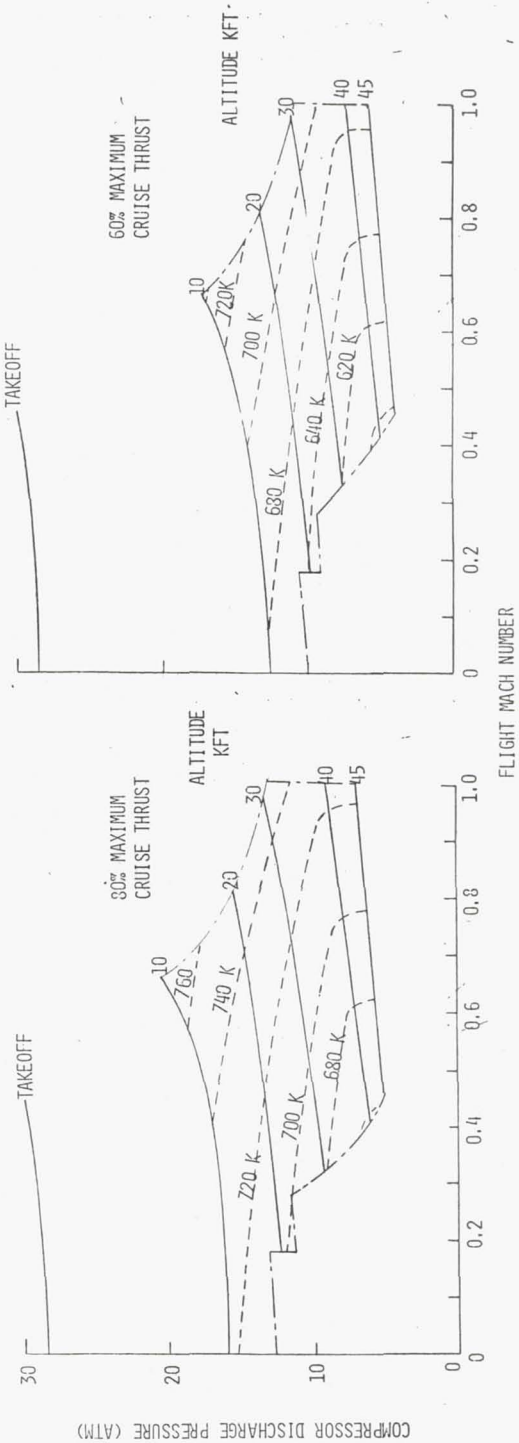
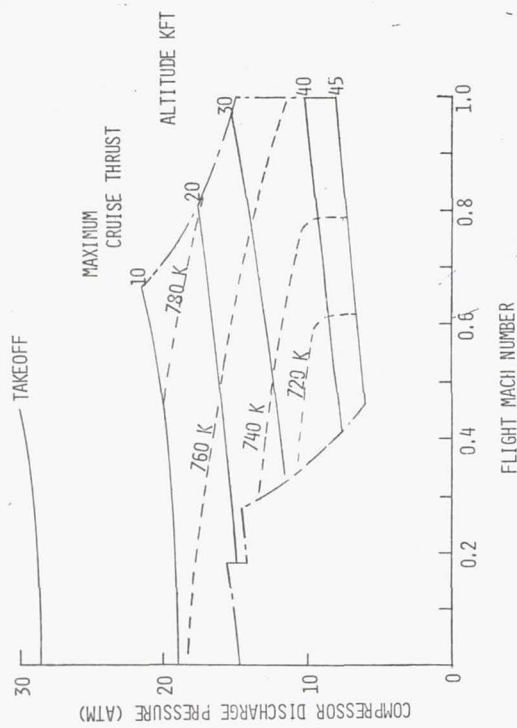


Figure 14. - Typical combustor inlet conditions for cruise flight.

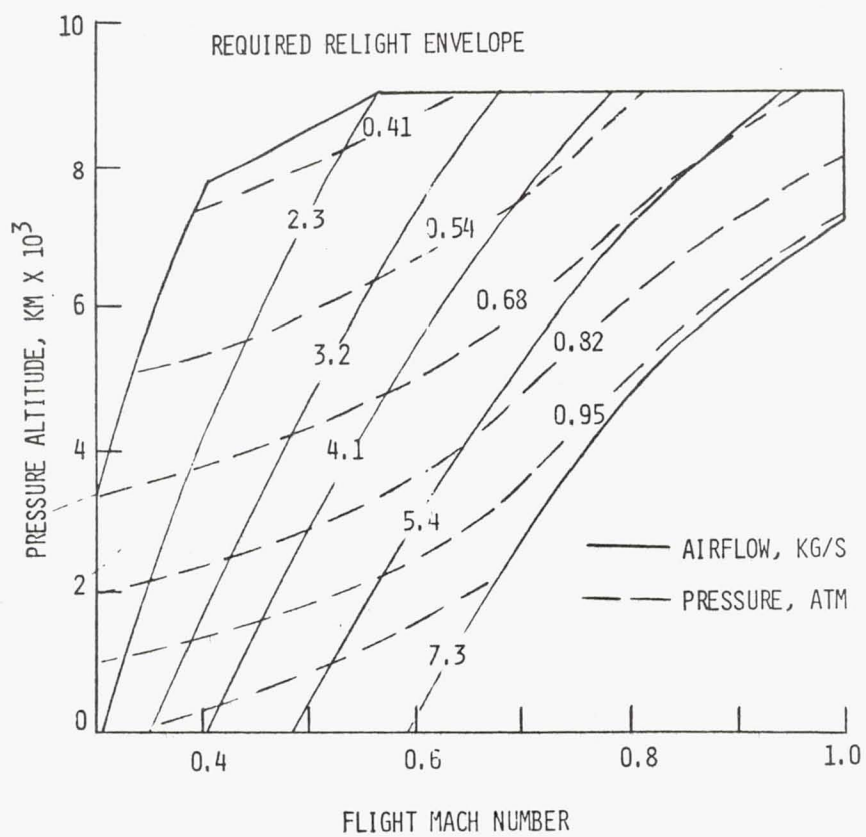


Figure 15. - Typical combustor conditions required for altitude relight.

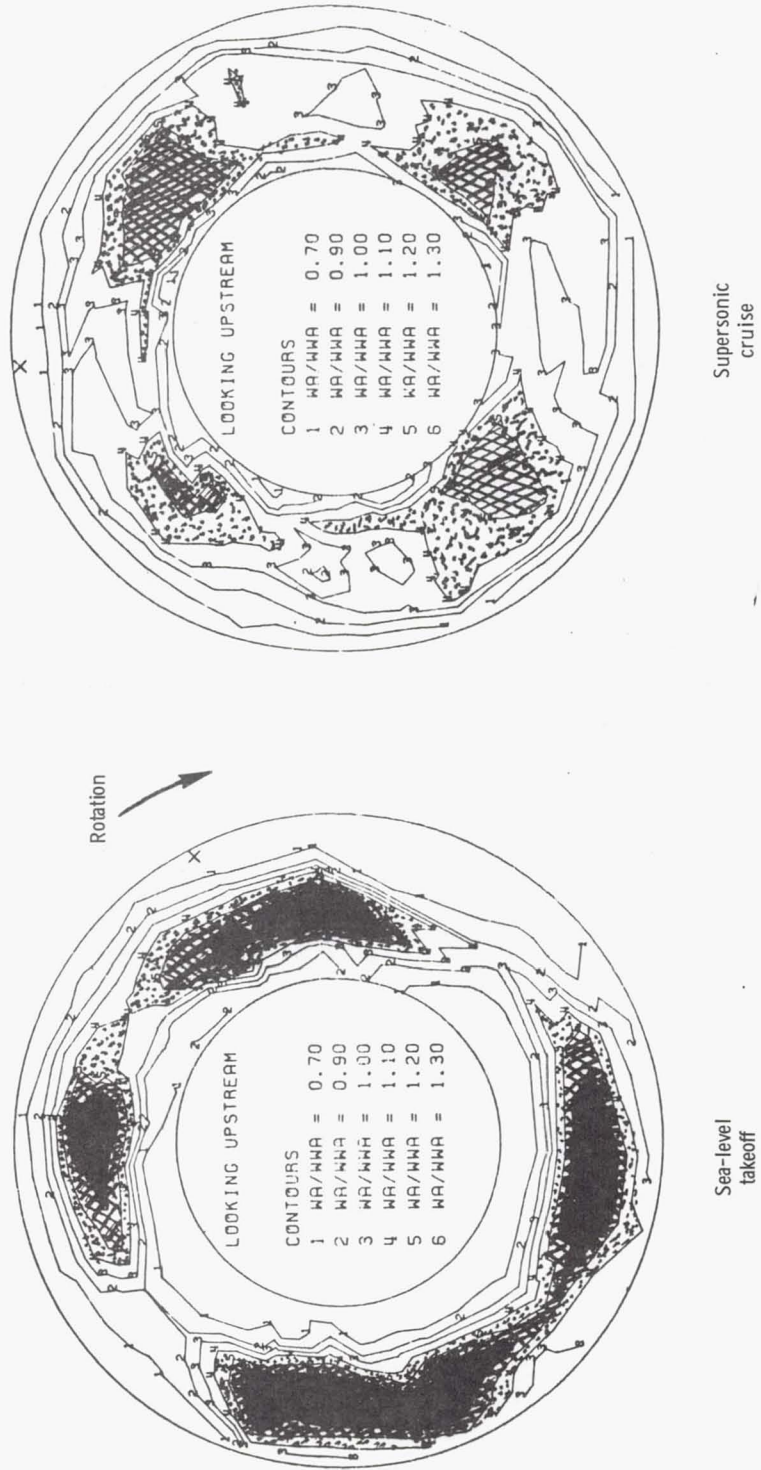


Figure 16. - Compressor discharge flow maps of J-58 compressor rig for local to average mass flow (WA/WWA). Bill-of-material configuration; undistorted inlet flow.

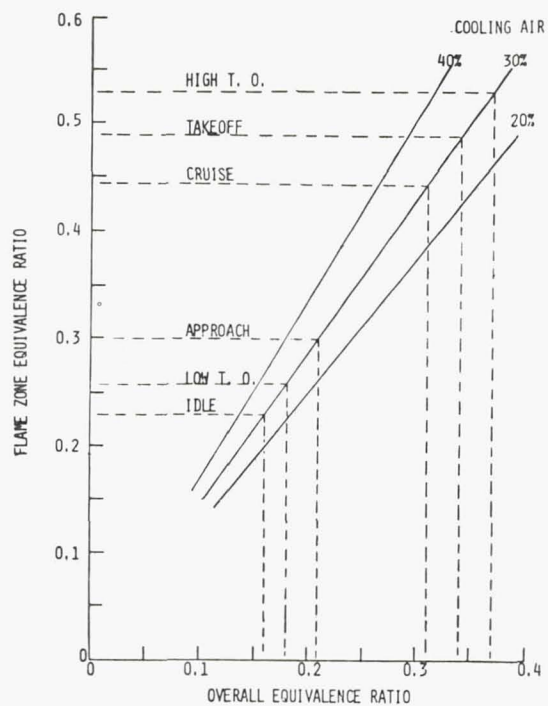


Figure 17. - Typical operating conditions - equivalence ratios.

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16. Abstract A 2-day workshop on lean premixed/prevaporized combustion was held on January 20 and 21, 1977, at the Lewis Research Center in Cleveland, Ohio. Participants met, discussed, and formulated recommendations on the status and application of lean premixed/prevaporized combustion to the aircraft gas turbine for the reduction of pollutant emissions. The approach taken by the NASA Stratospheric Cruise Emission Reduction Program (SCERP) in pursuing the lean premixed/prevaporized combustion technique was also discussed. The proceedings contains an overview of the SCERP program, the discussions and recommendations of the participants, and an overall summary.					
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